$SU(3)_{FLAVOR}$-ANALYSIS OF NONFACTORIZABLE CONTRIBUTIONS TO $D \rightarrow PP$ DECAYS

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ABSTRACT

We study charm D - meson decays to two pseudoscalar mesons in Cabibbo favored mode employing SU(3)-flavor for the nonfactorizable matrix elements. Using $D \rightarrow \bar{K}\pi$ and $D_s \rightarrow \bar{K}K$ to fix the reduced matrix elements, we obtain a consistent fit for η and η' emitting decays of D and D_s mesons.

It is now fairly established that the naive factorization model does not explain the data on weak hadronic decays of charm mesons. On one hand large $N_c \to \infty$ limit, which apparently was thought to be supported by D-meson phenomenology [1,2], has failed to explain B-meson decays, as B-meson data clearly demands [3] a positive value of the a_2-parameter. On the other hand even in D-meson decays, the two body Cabibbo favored decays of D^0 and D_s^+ involving η and η' in their final state have proven to be problematic for a universal choice of a_1 and a_2 [4]. Annihilation terms, if used to bridge the discrepancy between theory and experiment, require large form factors, particularly for $D \to \bar{K}^0 + \eta/\eta'$ and $D^0 \to \bar{K}^{*0} + \eta$ decays [4]. Further, factorization also fails to relate $D_s^+ \to \eta/\eta' + \pi^+/\rho^+$ decays with semileptonic decays $D_s^+ \to \eta/\eta' + e^+\nu$ [4,5] consistently.

Recently, there has been a growing interest in studying nonfactorizable terms for weak hadronic decays of charm and bottom mesons [6]. In an earlier work [7], we have searched for a systematics in the nonfactorizable contributions for various decays of D^0 and D^+ mesons involving isospin 1/2 and 3/2 final states. We observe that the nonfactorizable isospin 1/2 and 3/2 amplitudes have nearly the same ratio for $D \to \bar{K}\pi/\bar{K}\rho/\bar{K}^*\pi/\bar{K}a_1/\bar{K}^*\rho$ decay modes. In order to realize the full impact of isospin symmetry, and to relate D_s^+-decays with those of the nonstrange charm mesons, we generalize it to the SU(3)-flavor symmetry.

We analyze Cabibbo favored decays of D^0, D^+ and D_s^+ mesons to two pseudoscalar mesons. Determining the SU(3) reduced matrix elements from $D^+ \to \bar{K}^0\pi^+$ and $D_s^+ \to \bar{K}^0K^+$, we obtain a consistent fit for $D^0 \to \bar{K}+\pi/\eta/\eta'$ and $D_s^+ \to \pi + \eta/\eta'$ decays.

We start with the effective weak Hamiltonian

$$H_w = \tilde{G}_F[c_1(\bar{u}d)(\bar{s}c) + c_2(\bar{s}d)(\bar{u}c)], \tag{1}$$

where $\tilde{G}_F = \frac{G_F}{\sqrt{2}} V_{ud} V_{cs}^*$ and $\bar{q}_1 q_2 \equiv \bar{q}_1 \gamma_\mu (1-\gamma_5) q_2$ represents color singlet $V-A$ current and the QCD coefficients at the charm mass scale are

$$c_1 = 1.26 \pm 0.04, \qquad c_2 = -0.51 \pm 0.05. \tag{2}$$

Separating the factorizable and nonfactorizable parts, the matrix element of the operator $(\bar{u}d)(\bar{s}c)$ in eq. (1) between initial and final states can be written as

$$\begin{aligned} < P_1 P_2 | (\bar{u}d)(\bar{s}c) | D > &= < P_1 | (\bar{u}d) | 0 >< P_2 | (\bar{s}c) | D > \\ &+ < P_1 P_2 | (\bar{u}d)(\bar{s}c) | D >_{nonfac} . \end{aligned} \tag{3}$$

Using the Fierz identity

$$(\bar{u}d)(\bar{s}c) = \frac{1}{N_c}(\bar{s}d)(\bar{u}c) + \frac{1}{2}\sum_{a=1}^{8}(\bar{s}\lambda^a d)(\bar{u}\lambda^a c), \tag{4}$$

where $\bar{q}_1 \lambda^a q_2 \equiv \bar{q}_1 \gamma_\mu (1-\gamma_5) \lambda^a q_2$ represents color octet current, the nonfactorizable part of the matrix element in eq.(3) can be expanded as

$$\begin{aligned} < P_1 P_2 | (\bar{u}d)(\bar{s}c) | D >_{nonfac} &= \frac{1}{N_c} < P_2 | (\bar{s}d) | 0 >< P_1 | (\bar{u}c) | D > \\ + \frac{1}{2} < P_1 P_2 | \sum_{a=1}^{8} (\bar{s}\lambda^a d)(\bar{u}\lambda^a c) | D >_{nonfac} &+ \frac{1}{N_c} < P_1 P_2 | (\bar{s}d)(\bar{u}c) | D >_{nonfac} . \end{aligned} \tag{5}$$

Performing a similar treatment to the other operator $(\bar{s}d)(\bar{u}c)$ in eq.(1), the decay amplitude becomes

$$\begin{aligned} < P_1 P_2 | H_w | D > &= \tilde{G}_F [a_1 < P_1 | (\bar{u}d) | 0 >< P_2 | (\bar{s}c) | D > \\ &+ a_2 < P_2 | (\bar{s}d) | 0 >< P_1 | (\bar{u}c) | D > \\ &+ c_2 (< P_1 P_2 | H_w^8 | D > + < P_1 P_2 | H_w^1 | D >)_{nonfac} \end{aligned}$$

$$+c_1(< P_1P_2|\tilde{H}_w^8|D> + < P_1P_2|\tilde{H}_w^1|D>)_{nonfac}\ ], \tag{6}$$

where

$$a_{1,2} = c_{1,2} + \frac{c_{2,1}}{N_c}, \tag{7}$$

$$\begin{aligned} H_w^8 &= \frac{1}{2}\sum_{a=1}^{8}(\bar{s}\lambda^a d)(\bar{u}\lambda^a c), \ \ \tilde{H}_w^8 &= \frac{1}{2}\sum_{a=1}^{8}(\bar{u}\lambda^a d)(\bar{s}\lambda^a c); \\ H_w^1 &= \frac{1}{N_c}(\bar{s}d)(\bar{u}c), \ \ \tilde{H}_w^1 &= \frac{1}{N_c}(\bar{u}d)(\bar{s}c). \end{aligned} \tag{8}$$

Thus nonfactorizable effects arise through the Hamiltonian made up of color-octet currents (H_w^8 and $\tilde{H}_w^8$) and also of color singlet currents (H_w^1 and $\tilde{H}_w^1$).

Matrix elements of the first and the second terms in eq. (6) can be calculated using the factorization scheme [1]. These are given in Table I. So long as one restricts to the color singlet intermediate states, remaining terms in eq.(6) are ignored and one usually treats a_1 and a_2 as input parameters in place of using $N_c = 3$ in reality. It is generally believed [1, 8] that the $D \to \bar{K}\pi$ decays favour $N_c \to \infty$ limit, i.e.,

$$a_1 \approx 1.26, \qquad a_2 \approx -0.51. \tag{9}$$

However, it has been shown that this does not explain all the decay modes of charm mesons [4,5]. For instance, the observed $D^0 \to \bar{K^0}\eta$ and $D^0 \to \bar{K^0}\eta'$ decay widths are considerably larger than those predicted in the spectator quark model. Also in $D \to PV$ mode, measured branching ratios for $D^0 \to \bar{K^{*0}}\eta$, $D_s^+ \to \eta/\eta' + \rho^+$, are higher than those predicted by the spectator quark diagrams. For $D_s^+ \to \eta/\eta' + \pi^+$, though factorization can account for substantial part of the measured branching ratios, it fails to relate them to corresponding semileptonic decays $D_s^+ \to \eta/\eta' + e^+\nu$ consistently [4,5]. In addition to the spectator quark diagram, factorizable W-exchange or W-annihilation diagrams may contribute to the weak nonleptonic decays of D mesons. However,

for $D \to PP$ decays, such contributions are helicity suppressed [1]. For D meson decays, these are futher color-suppressed as these involve QCD coefficient c_2, whereas for $D_s^+ \to PP$ decays these vanish [4] due to the conserved vector (CVC) nature of isovector current ($\bar{u}d$). Therefore, it is desirable to investigate nonfactorizable contributions more seriously.

It is well known that nonfactorizable terms cannot be determined unambiguiously without making some assumptions [6] as these involve nonperturbative effects arising due to soft-gluon exchange. We thus employ SU(3)-flavor-symmetry [9] to handle these matrix elements. In the SU(3) framework, the weak Hamiltonians H_w^8, $\tilde{H}_w^8$, H_w^1 and $\tilde{H}_w^1$ for Cabibbo-enhanced mode behave like H_{13}^2 component of 6^* and 15 representations of the SU(3). Since H_w^8 and $\tilde{H}_w^8$ transform into each other under interchange of u and s quarks, which forms V-spin subgroup of the SU(3), we assume the reduced amplitudes to follow

$$< P_1P_2||\tilde{H}_w^8||D >=< P_1P_2||H_w^8||D > . \tag{10}$$

Then, the matrix elements $< P_1P_2|H_w^8|D >$ can be considered as *weak spurion* $+ D \to P + P$ scattering process, whose general structure can be written as

$$\begin{aligned} < P_1P_2|H_w^8|D > \quad &= \quad b_1(P_a^m P_m^c P^b)H^a_{[b,c]} + d_1(P_a^m P_m^c P^b)H^a_{(b,c)} \\ &\quad + e_1(P_m^b P_a^c P^m)H^a_{(b,c)} + f_1(P_m^m P_a^b P^c)H^a_{(b,c)} \end{aligned} \tag{11}$$

where P^a denotes triplet of D-mesons $P^a \equiv (D^0,\ D^+,\ D_s^+)$ and P_b^a denotes $3 \bigotimes 3$ matrix of uncharmed pseudoscalar mesons,

$$P_b^a \quad = \quad \begin{pmatrix} P_1^1 & \pi^+ & K^+ \\ \pi^- & P_2^2 & K^0 \\ K^- & \bar{K}^0 & P_3^3 \end{pmatrix} \tag{12}$$

with

$$P_1^1 \quad = \quad \frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} + \frac{\eta_0}{\sqrt{3}},$$

$$
\begin{aligned}
P_2^2 &= -\frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} + \frac{\eta_0}{\sqrt{3}}, \\
P_3^3 &= -\frac{2\eta_8}{\sqrt{6}} + \frac{\eta_0}{\sqrt{3}}.
\end{aligned}
$$

Particle data group [10] defines the physical $\eta - \eta'$ mixing as

$$
\eta = \eta_8 \cos\phi - \eta_0 \sin\phi,
$$

$$
\eta' = \eta_8 \sin\phi + \eta_0 \cos\phi, \tag{13}
$$

where $\phi = -10^0$ and $\phi = -19^0$ follow from the quadratic mass formula and the two photon decays widths respectively [10]. We employ the following basis [4]

$$
\begin{aligned}
\eta &= \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\sin\theta - (s\bar{s})\cos\theta, \\
\eta' &= \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\cos\theta + (s\bar{s})\sin\theta,
\end{aligned} \tag{14}
$$

where θ is given by

$$
\theta = \theta_{ideal} - \phi. \tag{15}
$$

Performing a similar treatment for H_w^1 and $\tilde{H}_w^1$, i.e.

$$
< P_1 P_2 || \tilde{H}_w^1 || D > \; = \; < P_1 P_2 || H_w^1 || D >, \tag{16}
$$

the matrix elements $< P_1 P_2 | H_w^1 | D >$ are obtained from

$$
\begin{aligned}
< P_1 P_2 | H_w^1 | D > \; = \; & b_2 (P_a^m P_m^c P^b) H^a_{[b,c]} + d_2 (P_a^m P_m^c P^b) H^a_{(b,c)} \\
& + e_2 (P_m^b P_a^c P^m) H^a_{(b,c)} + f_2 (P_m^m P_a^b P^c) H^a_{(b,c)}
\end{aligned} \tag{17}
$$

Since the C.G. coefficients appearing in the eqs. (11) and (17) are the same, the unknown reduced amplitudes get combined as

$$
b = b_1 + b_2, \;\; d = d_1 + d_2, \;\; e = e_1 + e_2, \;\; f = f_1 + f_2, \tag{18}
$$

when the matrix elements are substituted in eq.(6).

There exists a straight correspondence between the terms appearing in (11) and (17) and various quark level processes. The first two terms, involving the coefficients $b's$ and $d's$, represent W-annihilation or W-exchange diagrams. Notice that unlike factorizable W-exchange or W-annihilation diagrams, these diagrams are not suppressed on the basis of the helicity arguments due to the involvement of gluons. The third term, having coefficient $e's$, represents spectator quark like diagram where the uncharmed quark in the parent D-meson flows into one of the final state mesons. The last term is like a hair-pin diagram, where $q\bar{q}$ generated in the process hadronizes to one of the final state mesons. Thus obtained nonfactorizable contributions to various $D \to PP$ decays are given in Table II.

Now we proceed to determine the SU(3) reduced amplitudes b, d, e, f. First, we calculate the factorizable contributions to various decays using $N_c = 3$, which yields

$$a_1 = 1.09, \quad a_2 = -0.09 \tag{19}$$

For the form factors, we use

$$F_0^{DK}(0) = 0.76, \quad F_0^{D\pi}(0) = 0.83, \tag{20}$$

as guided by the semileptonic decays [8, 12], and

$$\begin{aligned} F_0^{D\eta}(0) = 0.68, \quad F_0^{D\eta'}(0) = 0.65, \\ F_0^{D_s\eta}(0) = 0.72, \quad F_0^{D_s\eta'}(0) = 0.70, \end{aligned} \tag{21}$$

from the BSW model [1]. Numerical values of the factorizbale amplitudes are given in col (iii) of Table I.

$D \to \bar{K}\pi$ decays involve elastic final state interactions (FSI) whereas the remaining decays are not affected by them. As a result, the isospin amplitudes

1/2 and 3/2 appearing in $D \to \bar{K}\pi$ decays develop different phases;

$$\begin{aligned} A(D^0 \to K^-\pi^+) &= \frac{1}{\sqrt{3}}[A_{3/2}e^{i\delta_{3/2}} + \sqrt{2}A_{1/2}e^{i\delta_{1/2}}], \\ A(D^0 \to \bar{K}^0\pi^0) &= \frac{1}{\sqrt{3}}[\sqrt{2}A_{3/2}e^{i\delta_{3/2}} - A_{1/2}e^{i\delta_{1/2}}], \\ A(D^+ \to \bar{K}^0\pi^+) &= \sqrt{3}A_{3/2}e^{i\delta_{3/2}}. \end{aligned} \tag{22}$$

which yield the following phase independent [7,11] expressions:

$$\begin{aligned} |A(D^0 \to K^-\pi^+)|^2 + |A(D^0 \to \bar{K}^0\pi^0)|^2 &= |A_{1/2}|^2 + |A_{3/2}|^2, \\ |A(D^+ \to \bar{K}^0\pi^+)|^2 &= 3|A_{3/2}|^2. \end{aligned} \tag{23}$$

These relations allow one to work without the phases. Writing the total decay amplitude as sum of factorizable and nonfactorizable parts

$$A(D \to \bar{K}\pi) = A^f(D \to \bar{K}\pi) + A^{nf}(D \to \bar{K}\pi), \tag{24}$$

we obtain

$$A^{nf}_{1/2} = \frac{1}{\sqrt{3}}\{\sqrt{2}A^{nf}(D^0 \to K^-\pi^+) - A^{nf}(D^0 \to \bar{K}^0\pi^0)\}, \tag{25}$$

$$\begin{aligned} A^{nf}_{3/2} &= \frac{1}{\sqrt{3}}\{A^{nf}(D^0 \to K^-\pi^+) + \sqrt{2}A^{nf}(D^0 \to \bar{K}^0\pi^0)\}, \\ &= \frac{1}{\sqrt{3}}\{A^{nf}(D^+ \to \bar{K}^0\pi^+)\}. \end{aligned} \tag{26}$$

The last relation (26) leads to the following constraint:

$$\frac{b+d}{e} = \frac{c_1 + c_2}{c_2 - c_1} = -0.424 \pm 0.042. \tag{27}$$

Experimental value $B(D^+ \to \bar{K}^0\pi^+) = 2.74 \pm 0.29\%$ yields, up to a scale factor $\tilde{G}_F$,

$$e = -0.094 \pm 0.027\, GeV^3. \tag{28}$$

This in turn predicts sum of the branching ratios of $D^0 \to \bar{K}\pi$ decay modes,

$$B(D^0 \to K^-\pi^+) + B(D^0 \to \bar{K}^0\pi^0) = 6.30 \pm 0.67\% \quad (6.06 \pm 0.30\%\ Expt.) \tag{29}$$

in good agreement with experiment. Using the experimental value of $B(D_s^+ \to \bar{K}^o K^+) = 3.5 \pm 0.7\%$, we find (in GeV^3)

$$b = +0.080 \pm 0.026, \tag{30}$$

$$d = -0.040 \pm 0.026. \tag{31}$$

Note that the unknown reduced amplitude f appears only in decays involving η and η' in the final state. We find that experimental values of these decay rates require (in GeV^3):

$$\begin{aligned}
f &= -0.145 \pm 0.077 \quad \text{for} \quad D^0 \to \bar{K}^0\eta, \\
f &= -0.115 \pm 0.012 \quad \text{for} \quad D^0 \to \bar{K}^0\eta', \\
f &= -0.104 \pm 0.163 \quad \text{for} \quad D_s^+ \to \eta\pi^+, \\
f &= -0.081 \pm 0.073 \quad \text{for} \quad D_s^+ \to \eta'\pi^+.
\end{aligned} \tag{32}$$

In Tables III, we calculate branching ratios for all the four η, η' emitting decay modes for different choice of f, for $\phi = -10^o$ and -19^o. It is clear that for $f = -0.12$ and $\phi = -10^o$, all the branching ratios match well with experiment. For the sake of comparison with factorizable terms, nonfactorizable contributions to various modes for $f = -0.12$ are given in column (iii) of the Table II. Color-suppressed decays obviously require large nonfactorizable contributions.

Acknowledgments

The author thanks A.N. Kamal for providing support from a grant from NSERC, Canada during his stay at the University of Alberta, Canada. He also thanks the Theoretical Physics Institute, Department of Physics, University of Alberta, where part of the work was done, for their hospitality.

Table I

Spectator-quark decay amplitudes ($\times \tilde{G}_F \ GeV^3$)

Process	Amplitude	$\phi = -10^0$	$\phi = -19^0$
$D^+ \to K^0\pi^+$	$a_1 f_\pi(m_D^2 - m_K^2)F_0^{DK}(m_\pi^2)$ $+ a_2 f_K(m_D^2 - m_\pi^2)F_0^{D\pi}(m_K^2)$	+0.311	+0.311
$D^0 \to K^-\pi^+$	$a_1 f_\pi(m_D^2 - m_K^2)F_0^{DK}(m_\pi^2)$	+0.354	+0.354
$D^0 \to \bar{K}^0\pi^0$	$\frac{1}{\sqrt{2}} a_2 f_K(m_D^2 - m_\pi^2)F_0^{D\pi}(m_K^2)$	-0.030	-0.030
$D^0 \to \bar{K}^0\eta$	$\frac{1}{\sqrt{2}} a_2 sin\theta f_K(m_D^2 - m_\eta^2)F_0^{D\eta}(m_K^2)$	-0.016	-0.019
$D^0 \to \bar{K}^0\eta'$	$\frac{1}{\sqrt{2}} a_2 cos\theta f_K(m_D^2 - m_{\eta'}^2)F_0^{D\eta'}(m_K^2)$	-0.013	-0.010
$D_s^+ \to \bar{K}^0K^+$	$a_2 f_K(m_{D_s}^2 - m_K^2)F_0^{D_sK}(m_K^2)$	-0.035	-0.035
$D_s^+ \to \pi^0\pi^+$	0	0	0
$D_s^+ \to \eta\pi^+$	$-a_1 cos\theta f_\pi(m_{D_s}^2 - m_\eta^2)F_0^{D_s\eta}(m_\pi^2)$	-0.261	-0.216
$D_s^+ \to \eta'\pi^+$	$a_1 sin\theta f_\pi(m_{D_s}^2 - m_{\eta'}^2)F_0^{D_s\eta'}(m_\pi^2)$	+0.213	+0.243

Table II

Nonfactorizable contributions to $D \to PP$ decays ($\times \tilde{G}_F \ GeV^3$)

Process	Amplitude	$\phi = -10^0$	$\phi = -19^0$
$D^+ \to K^0\pi^+$	$2(c_1 + c_2)\, e$	-0.141	-0.141
$D^0 \to K^-\pi^+$	$c_2\,(b + d + e)$	+0.028	+0.028
$D^0 \to \bar{K}^0\pi^0$	$\frac{1}{\sqrt{2}} c_1\,(-b - d + e)$	-0.119	-0.119
$D^0 \to \bar{K}^0\eta$	$c_1[\frac{sin\theta}{\sqrt{2}}\,(b + d + e + 2f) \ - \ cos\theta(b + d + f)]$	-0.115	-0.154
$D^0 \to \bar{K}^0\eta'$	$c_1[\frac{cos\theta}{\sqrt{2}}\,(b + d + e + 2f) \ + \ sin\theta(b + d + f)]$	-0.256	-0.235
$D_s^+ \to \bar{K}^0K^+$	$c_1\,(-b + d + e)$	-0.268	-0.268
$D_s^+ \to \pi^0\pi^+$	0	0	0
$D_s^+ \to \eta\pi^+$	$c_2[\sqrt{2} sin\theta\,(-b + d + f) \ - \ cos\theta(e + f)]$	+0.046	+0.076
$D_s^+ \to \eta'\pi^+$	$c_2[\sqrt{2} cos\theta\,(-b + d + f) \ + \ sin\theta(e + f)]$	+0.199	+0.189

Table III

Branching (%) of η/η' emitting decays including nonfactorization terms

Decay	$\phi = -10^o$			$\phi = -19^o$			Expt.
	$f = -0.10,$	$-0.12,$	-0.14	$f = -0.10,$	$-0.12,$	-0.14	
$D^0 \to \eta \bar{K}^0$	0.53	0.59	0.66	0.86	1.02	1.19	0.68±0.11
$D^0 \to \eta' \bar{K}^0$	1.28	1.81	2.43	1.04	1.51	2.06	1.66±0.29
$D_s^+ \to \eta \pi^+$	1.93	1.87	1.82	0.86	0.80	0.73	1.9±0.4
$D_s^+ \to \eta' \pi^+$	5.17	5.64	6.13	5.73	6.22	6.72	4.7±1.4

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